NAME:____ **PART A**

MECH 372 Space Systems Design and Engineering II
Quiz 1

Part A - Closed Book (45 points)

1. (7) Match each of the missions listed with the single most compelling justification for using a spacecraft in order to achieve the stated mission. Each justification may be used once, more than once, or not at all; but for any one mission, you may only list one justification (or it will be marked wrong).

D_____ Mars Exploration Rovers
F_____ SpaceShip 2 (buy a ticket for sub-orbital human space flight)
A_____ GOES weather satellite
C_____ A protein growth experiment requiring microgravity
B_____ Hubble space telescope
G_____ Sputnik
A_____ Direct broadcast radio satellite

A. Global view of Earth
B. Above Earth's atmosphere
C. Space environmental characteristics
D. In situ characterization and exploration
E. Exploitation of resources
F. Space Tourism
G. Pride and distinction

2. (2) What would the payload be on a typical photoreconnaissance satellite? List at least 2 different, specific components that would be plausible payload components for such a system.

Could include camera, filter wheels, optics, on-board image processing computers, etc.

3. (1) State Kirchhoff's Current Law (this should be a written statement that states the general law – not a specific example with a diagram and/or an equation):

Sum of the currents into a node equals zero

4. (2) Radiation damage to a circuit has been known to cause short circuits. What is a short circuit (be precise) and why is a short circuit a potentially dangerous condition for a satellite?

No load circuit – direct connection across a source. This can lead to very high current that can damage components, rapidly deplete stored energy, etc.

5. (1) A power subsystem supplies 500W of power at 28V. How much current is available?

500/28=17.86A

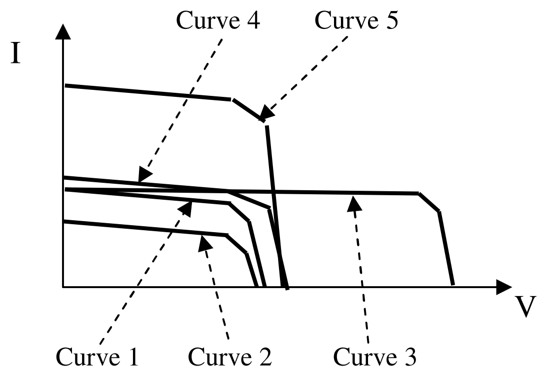
6. (2) Why is it beneficial to operate a solar array at the "knee" of its V-I curve? Will the array naturally operate at this point?

That point represents the maximum power generation
No – it will not. It will operate at whatever voltage is dictated by the load

7. (2) Give an example of a condition that would cause a "load shed" to occur. In addition, state what happens during a "load shed" process.

Loss of sun lock and a low stored power condition
Turn off all unnecessary loads in order to save power.

8. (4) In the set of solar cell IV curves given below, Curve 1 is the IV curve for a standard solar cell operating in standard conditions (one solar illumination, room temperature, etc.). For each of the other curves, select the description that best depicts what that curve would represent; each curve represents a different case listed in A-D (all answers from A-D are used once and only once).



D_____ Curve 2 A. 2 standard cells in parallel

B_____ Curve 3 B. 2 standard cells in series

C_____ Curve 4 C. 1 standard cell at -100°C

A_____ Curve 5 D. 1 standard cell at ~ 2/3 illumination

9. (2) In the lecture and the homework assignments, we typically considered four primary sources of thermal energy in order to perform thermal balance computations (these did not include particle heating). List these four ***sources***.

Direct solar, albedo, earth IR, and internal heating

10. (2) What is the "beta" angle for a spacecraft's orbit (be explicit about how this angle is defined)? Explain why it is important for a thermal analysis by identifying the two primary thermal inputs (two of the four from question 10) that are significantly affected by this angle.

Beta is an **angular measurement** of how the orbit plane is inclined with respect to the solar vector. Its value is associated with the how close the satellite's orbit comes to passing over the **subsolar** point as well as the **duration of eclipses**. These, in turn, **affect albedo fractions** and the amount of **direct solar** thermal input, which are two significant contributors to a satellite's thermal environment.

11. (20) True or False: Circle the appropriate solution for each individual question.

T F a. Having a global or wide field of view is the primary competitive motivation for the vast majority of communications, navigation and Earth observing spacecraft.

T F b. A capacitor stores energy in an electric field, and it has a I-V relationship that is a function of time.

T F c. The decimal number 42 is represented in binary by the following 8 bits: 00101010 (the most significant bit is on the left):

T F d. In low Earth orbit, a single eclipse may last for up to approximately 90 minutes.

T F e. Solar cell efficiency does not depend on the materials used to make the cells; rather, it is primarily a function of the cell's level of illumination and its temperature.

T F f. The term "multi-junction cells" is used to describe separate cells wired in a parallel configuration on a solar panel.

T F g. RTGs (radioisotope thermoelectric generators) use nuclear fission to produce electrical power.

T F h. RTG power output is usually actively controlled to provide the specific level of power required by the satellite's loads.

T F i. A battery typically operates based on a "redox" process. Oxidation is part of such a process. Oxydation is a process by which a molecule, atom or ion looses electrons.

T F j. In the lecture and slides, the term "secondary battery" was used to refer to a back-up battery that is used for redundancy when a "primary battery" fails.

T F k. A NiCad battery typically has a very predictable discharge profile in which voltage drops linearly over time, assuming a standard discharge rate and temperature appropriate for the battery.

T F l. Shunt regulators prevent too much power from going to satellite loads by shorting portions of the solar array to divert current flow.

T F m. Survival temperature requirements are typically more restrictive (have a small range) than the range defined by operating temperature requirements.

T F n. From a thermal design perspective, radiation is a process by which heat is transferred via electromagnetic waves.

T F o. The symbols α and ε are defined as being the absorptivity and the emissivity of a material's surface, respectively. However, in practice, spacecraft thermal engineers often use α to represent both absorptivity and emissivity for visible wavelength ranges, while ε is used to represent both absorptivity and emissivity for infrared wavelength ranges.

T F p. From the point of view of thermal analysis, a satellite in a "noon-midnight" orbit has a Beta angle of 0°.

T F q. Black paints/coatings will generally have a higher absorptivity to emissivity ration than white paints/coatings.

T F r. Experimental data shows that, in most cases, increasing the pressure on a joint between to materials will generally improve conduction between the materials.

T F s. Heat pipes use pumps and fans to move liquid and gases between different ends of the pipe in order to transfer heat from one end to the other.

T F t. When performing thermal environmental tests, "Acceptance" testing is typically more demanding than "Qualification" testing in terms of the temperature ranges used.

NAME:____ **PART B**

Part B - Open Book (35 points)

12. (5) A component that dissipates 100W is attached to a 0.16 m^2 radiator that sees only deep space and which has an emissivity of 0.9. The area of the attachment between the two components is 0.01 m^2. The component is insulated on all sides other than the thermal coupling to the radiator such that all dissipated power flows to the radiator. Assume that the system is in steady state and that the component must be kept below 70°C. It is your job to determine the minimum joint conductance required in order to ensure this.

The system is in steady state. The transmitter is 70 deg C worse case (which is what you should assume for this problem given that you are finding min joint conductance), and 100W flows through the conductive joint to the radiator (no other flows given the insulation). The radiator is at some steady state temp (which you are not given, but which you can compute) and radiates all 100W.

So, to compute joint conductance we need deltaT, which means we need the radiator temp. So compute radiator temp first;

Radiator temperature can be found: $Q=e*sigma*(T_{rad})^4*A_{rad} \rightarrow T_{rad}=(100/[e*sigma*A_{rad}])^{1/4}$ = 333 deg K

Now, find joint conductance: $Q=h_c*A*(T_{comp}-T_{rad}) \rightarrow h_c = Q / (A*deltaT)$ = 1000 W/m^2K (given rounding and the small deltaT, I gave credit for most answers in the 900-1100 range (assuming the right process was used).

13. (5) Consider a battery pack consisting of 4 parallel strings of cells, with each string consisting of 15 cells in series. NiCad cells with a voltage of 1.2V and a capacity of 0.5 Amp-hrs are being used. What is the overall voltage of the battery pack? What is the Amp-hr rating of the overall battery pack? Assuming a Depth of Discharge policy of 50%, how long could this pack supply a constant current of 4 amps?

You need to remember that in series, voltages add and currents are equal; vice versa for parallel configurations. So:

Battery pack voltage: 15 cells x 1.2 V/cell = 18V
Battery pack rating: 4 strings x 0.5 Ahrs = 2 amp-hrs
Duration at 4 amps: 2 Ahrs @ 50% means 1 Ahr of use; @ 4 A, can get ¼ of an hour, so, 15 min

The following case is used for questions 14 and 15. Consider a spinning, cylindrical satellite that has a 1.5 meter diameter and a height of 2 meters. The satellite is in a circular, sun-synchronous, 1000 km altitude orbit that has β=90°. One of the circular ends of the satellite holds the Earth-referenced payload components and therefore always faces the Earth; the other circular end of the satellite always points away from the Earth.

14. (12) Solar Array Sizing. The satellite loads require a constant 600 W, and the power distribution/regulation's efficiency is 75% (regardless of charge/discharge mode). The body mounted solar array has cells mounted around the entire curved surface of the cylindrical structure. The array uses cells that are 28% efficient and which are mounted with a fill factor of 0.9. We will assume no losses due to temperature deviation or shadowing. The satellite has a mission life of 5 years, and the cells have a degradation factor of 3%/yr. We will assume that the solar illumination 1358 W/m^2.

a) How much power must the solar array generate during illumination?
The first 3 parts of this problem follow the slides very closely given that they provide a flat panel version of the solar array design process.
One issue was realizing that given β=90°, the satellite is always in the sun. So, there is no eclipse. Given that, the P_{SA} equation becomes trivial. So P_{SA}=600W/0.75=800W

b) What power density (W/m^2) is provided by the individual cells when they are fully illuminated (at beginning of life)?

This question concerns only the cells, with no consideration (yet) of putting cells into the arrays. This is used exactly the same way as on Slide 54 of the solar power lecture.

$P'_{cell} = .28*1358 = 380\ W/m^2$

c) For the moment, assume that the cells are placed on a planar solar array. Given the cell power density from part (b) as well as the packing factor and all degradations, what would the array's area need to be in order to meet the solar array power requirement from part (a) at the end of its 5 year life? Assume that the array is perfectly facing the sun for this question.

Continuing with the process outlined in the slides:

$P'=P'_{cell} * I_d *L_d = 380\ W/m^2 * 0.9* (0.97)^5 = 294\ W/m^2$

$A_{SA}=P_{SA}/P' = 2.72\ m^2$

Again – this is the area you would need at EOL to power the satellite if the array was a flat panel pointed perfectly at the sun

d) Now take into account the fact that this solar array is body mounted on the satellite's cylindrical surface. What total array surface area is required for the cylindrical installation?

Here is the only twist, but it is the same "projected area" conversation that we discussed many many times for solar inputs in the thermal lecture.

We are trying to find the area of the cylindrical version of the solar array. This wraps all the way around the cylinder and extends for some vertical fraction of the entire height of the satellite (unless it goes beyond, in which case the satellite isn't tall enough). Half will always be shadowed, and of the other half in the sun, the cells have varying angles to the sun. You could simply integrate… or realize that the equivalent area is the projected area of the cylinder, which is diameter times height. So – the insight here is that you basically calculated the necessary projected area in part c. So, if part c is the projected area, this area is the diameter of the satellite times the vertical extent of the panel.

The ratio of the related cylindrical area to this flat projected area is 2*pi*r*h / (2*r*h) = pi

So, we need pi * the area from part c (2.72 m^2) of cylindrical body area, which is 8.55 m^2

e) Is the satellite large enough to hold the required array?

The satellite has an external cylindrical section area of 2*pi*r*height=9.43 m^2, so yes, there IS enough area

15. (13) Single Node Thermal Analysis. Assume for now that the sides of the satellite are coated with white paint (α=0.15, ε=0.95) (ignore the fact that solar cells and other components are installed on the exterior of the satellite). The satellite is internally dissipating 500W. Assume that the Earth's radius is 6,378 km and that albedo may be ignored for this initial analysis.

a) How many Watts are absorbed by the satellite due to direct solar heating? ___________611 W

Very straightforward computation. But you must be sure to use the proper area. The sun "sees" the side of the cylinder, so the area is the diameter x height of the cylinder, which is 3 m^2

$\alpha = 0.15$, $J_s = 1358$, $A_s = 3$;

b) How many Watts are absorbed by the satellite due to Earth IR heating? (Hint: remember to consider the input to all sides of the spacecraft) ___________614 W

This requires that you compute the input for the circular end of the satellite directly pointed to the Earth and then also the cylindrical sides of the satellite which only see a portion of the Earth. These inputs require using Slide 24 for the view factors – as a result, I give full credit for a range of solutions based on the error in reading the right number off of this slide.

Note – the Slide 24 process for computing the factor is an ALTERNATE approach for using the inverse square law distance offset approach used on Slide 30. In fact, you had a homework problem that reinforced this notion. You use one or the other – not both. Furthermore, the Slide 30 approach is only good for perpendicular surfaces whereas the Slide 24 approach, while more ambiguous given the error bars on the lookup process, is good for any lambda angle. So – for this solution, I'll use the Slide 24 process. That said, you could use the Slide 30 process only for the circular end portion, and you would get about the same (I was within 5% when I tried this).

OK – so:

For the circular end facing the Earth: $\varepsilon = 0.95$, $A_s = 1.77$; $F \sim 0.77$; and so Q_{end}~306W (when I use the slide 30 approach, I get $J_{ir} = 177$, which gives me Q_{end}=298)

For the cylindrical sides: $\varepsilon = 0.95$, $A_s = 9.4$, F~ 0.2 (from slide for h/R=.16); and so Q_{sides}= 423W

So, the total IR input is the sum: ~729W (again, there is an acceptable range above and below this value as long as you followed the right process)

c) What is the temperature of the satellite? _____227 degrees K

This answer depended on your solutions for parts (a) and (b) – I tried to recomputed this for each of you based on whatever you had for those previous parts (I may very well have made a mistake, so let me know if you think I did). If you followed the right process using your numbers from (a) and (b) (whether they were right or not) then I gave you full credit.

A_{surf}= 2*pi*r^2 + 2*pi*r*h = 3.534 + 9.425 = 12.959 m^2

[611 W] + [729 W] + [500W] = 1725W = e * sigma * (A_{surf}) * T^4

d) Now, let's assume that you are going to choose a different value for α and ε such that the satellite's average temperature is 10°C. If you select a value of ε=0.4, what value of α should you select in order to achieve this temperature?

Like the previous part, this answer depended on your solutions for parts (a) and (b) – I tried to recomputed this for each of you based on whatever you had for those previous parts (I may very well have made a mistake, so let me know if you think I did). If you followed the right process using your numbers from (a) and (b) (whether they were right or not) then I gave you full credit.

You essentially want to use the thermal balance equation with the new value of emissivity and compute absorptivity:

$$\alpha\left(J_{sun}A_{sun} + J_{alb}A_{alb}\right) + \varepsilon J_{planet}A_{planet} + Q_{\text{int}} = \varepsilon\sigma T^4 A_{surf}$$

Using this in the context of this specific problem and with the numbers from parts (a) and (b):

Alpha*(Q_{sun}/0.15) + 0.4*(Q_{ir}/0.95) + 500 = 0.4* sigma*$(283)^4$*(12.959 m^2)

So, alpha = `[ [0.4*(5.67*10^-8)*(283^4)*12.959]-500-[0.4*Wir/0.95] ] / (Wsun/0.15)  where Wsun is from part (a) and Wir is from part (b)`

Alpha = 0.265

COMMENTS ON RESULTS AND GRADING

NOTE – I did all the grading myself. I concede that I may have made errors. I am happy to regrade any/all things that you think may have been misgraded. However – I INSIST that you first look at the solutions and double check your own work. If you STILL have the same issue, then come see me.

CLOSED BOOK
The closed book results were quite good.
Only a few questions seemed to missed by any significant number of people:

- #7: 5 people confused "load shed" for power emergencies with "shunting" power during excess production
- #20d: several answered T; but 90 min is the duration of an entire orbit for LEO, not the duration of an eclipse
- #20g: several answered T; but RTGs operate on decay and thermoelectric, not a fission process (in fact, we had a brief discussion on how RTGs were explicitly NOT a form of nuclear energy fission/fusion processes
- #20l: when shunting excess power, you don't short your solar arrays – we do NOT like shorts! Rather, you generally expend the excess power by powering heater-like devices out on the solar arrays to "shunt" the heat
- #20q: black coatings generally absorb and retain heat more than white coatings, so their ratios are typically higher… since we discussed this quite a bit, my thought is that the several of you who missed this simply got it backwards rather than it being a situation where you don't understand what is going on – but, if you really don't understand, come see me and we can certainly walk through it

For #2, I was looking for at least 2 specific payload items that would not be debatable as to whether they would be considered payload or bus. Most people said some version of a camera, but then a lot of you said things like a transmitter to download the information, or an attitude control system to point the satellite when taking pictures. These are traditionally bus items, but it could be debated as being payload if there was some sort of special version of these. So – I gave full credit for any such answers. But – for people who had clear cut payload components beyond a camera – like filter wheels, special optics, perhaps on-board image processing, etc. – I gave ½ pt extra credit.

OPEN BOOK
The results for questions 12 and 13 were great. Let me know if you have questions on the abbreviated solutions
For 14:

- A few of you didn't give me cell power density for b, but if I could find it in your calculations for whatever you gave me, I gave you full credit
- The most missed part (for the entire exam) was part d. In c, you computed the amount of array area that had to be completely illuminated and perpendicular to the sun at all time. In d, I ask that, given c, you now figure out what the array area around the cylindrical body needs to be in order to achieve the equivalent power production as in part c. All that was required was to realize that c was the exposed area of d; therefore, the geometric difference btw cylindrical surface area and the projected area of that surface is a factor of pi. So, part d is pi time part c. We discussed the body shape vs projected area issue quite a bit in the thermal part of the lecture, much less so in the power part. So – you needed to make the same connection here.

For 15:

- It was essential that you understood the relative orientation of the satellite to the sun and Earth. A circular end points to Earth. The cylindrical sides see a fraction of the Earth and a projected area sees the sun. The "other" circular end points away from both.
- For part a, about a third of the class used the wrong area – the projected area seen by the sun is h*d of the cylinder = $3m^2$
- For part b, about 2/3 of the class did something wrong (kudos to several of you who got it all right). You needed to find the IR input to the circular end and add that to the IR input to the sides (which only see a small fraction of the Earth). Typical errors were not including both, including the "other" circular end facing deep space, incorrectly determining or ignoring view factors, etc. For the view factor lookup, I was very forgiving with the range of acceptable values. Some people 'double booked' the view factor by using both the geometric lookup as well as the distance offset approach.
- For parts c and d, I TRIED to check everyone's numbers based on whatever they got for parts a and b. If you were consistent, you got full credit. I may very well have made an error doing this (given that the

computations are tedious and I redid it for all of you) – so by all means, if you disagree with me, PLEASE first double check your work, and if you still disagree come see me and I'll redo my version.